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TECHNICAL NOTE

ELECTROMAGNETIC PULSE (EMP) FROM THE MAGNETIC BUBBLE SOURCE AS A DISCRIMINATOR OF UNDERGROUND NUCLEAR EXPLOSIONS, INCLUDING CAVITY DECOUPLING

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The purpose of this technical note is to highlight the potential value of combined seismic and extremely low frequency (ELF) measurements for close-in monitoring at known or suspect nuclear test sites. This report includes summaries of previous ELF measurements made by Lawrence Livermore National Laboratory at the Nevada Test Site and calculations made at the Zababakhin Institute at Snezhinsk, Russian Federation. A technical plan to develop the approach is recommended. The development could be carried out under the auspices of international bilateral or multilateral (for example, P-5) agreements. The combination of local seismic and ELF measurements at known or suspect nuclear test sites, if developed, would provide a robust detection capability for very low-yield nuclear tests, including the possibility of testing in cavities to muffle (decouple) the seismic signal.

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Electromagnetic pulse, EMP, extremely low frequency, ELF, Lawrence Livermore National Laboratory, Zababakhin Institute, U.S. Department of State International Science and Technology Center, international bilateral or multilateral, P-5, UGT

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ABSTRACT

The purpose of this technical note is to highlight the potential value of combined seismic and extremely low frequency (ELF) measurements for close-in monitoring at known or suspect nuclear test sites. This report includes summaries of previous ELF measurements made by Lawrence Livermore National Laboratory at the Nevada Test Site and calculations made at the Zababakhin Institute at Snezhinsk, Russian Federation. A technical plan to develop the approach is recommended. The development could be carried out under the auspices of international bilateral or multilateral (e.g., P-5) agreements. The combination of local seismic and ELF measurements at known or suspect nuclear test sites, if developed, would provide a robust detection capability for very low-yield nuclear tests, including the possibility of testing in cavities to muffle (decouple) the seismic signal.

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1. INTRODUCTION

The Comprehensive Nuclear Test Ban Treaty has stimulated renewed interest in monitoring for nuclear explosions, especially underground tests of nuclear devices including full-up weapons or components at yields well below 1 kt. Monitoring at low yields (<<1 kt) requires close-in detection at known or suspect test sites. Transparency or confidence building measures likely will consider at least the possibility of close-in monitoring. This technical note focuses on the electromagnetic pulse (EMP) produced by an underground nuclear explosion. In particular, the extremely low frequency (ELF) induction fields produced by the so-called magnetic bubble associated with the initial high-conductivity, high-temperature, high-pressure region of plasma are evaluated as a candidate for close-in monitoring. Relevant experimental data collected by Lawrence Livermore National Laboratory during underground tests at the Nevada Test Site and calculations performed at the Zababakhin Institute, Snezhinsk, Russian Federation, under sponsorship of the International Science and Technology Center are summarized. Estimates of the induced fields associated with the magnetic bubble are presented using a quasi-static magnetic dipole field model. The size of the initial plasma region is determined from the Continuous Reflectometry for Radius-Time Experiments (CORRTEX) empirical strong-shock scaling. The results of the evaluation indicate that, if developed, a combination of close-in seismic and ELF monitoring would provide a robust detection capability against low-yield nuclear explosions, either fully coupled seismically to the surrounding underground geologic environment or seismically decoupled in a cavity. When fully coupled, an underground nuclear explosion produces a strong seismic signal and a relatively weak ELF pulse. If an underground nuclear explosion of the same yield is carried out in a cavity, a relatively weak seismic signal is produced but with at least an order of magnitude stronger ELF pulse. In either case, detection of an ELF pulse from an underground explosion would be evidence that the explosion was nuclear in origin.

2. MAGNETIC BUBBLE EMP

2.1 Magnetic Bubble Source

It has been known for at least 50 yr that nuclear explosions produce a region of highly conductive plasma that:

- Causes a transient magnetic dipole to be formed by expansion of a plasma that excludes the Earth's B-field from the highly conductive volume

  which in turn,

- Induces a transient anomaly in the Earth's magnetic field referred to as
  - Magnetic hydrodynamic (MHD)-EMP (E3) from high-altitude explosions
  - A component of late-time EMP from atmospheric explosions
  - Magnetic bubble in underground explosions

2.2 Magnetic Bubble EMP From Underground Tests (UGTs)

Characteristic features include:

- Small fluctuation in the ambient B-field: ~10-100 pT
- Low-frequency, short-lived pulse: <<100 Hz, <1 s
- Nuclear pulse different from chemical: larger, smoother
- Detectable at short range: <10 km
- Increases with cavity size (decoupling): ~100x

Therefore:

  - Not useful as a device diagnostic measurement (even close-in)
  - May discriminate nuclear from chemical explosions, even in cavities
  - Combined with seismic, potentially useful as a close-in transparency (or confidence building) measure at known (or suspect) test sites

3. SWEENEY NTS MEASUREMENTS[1]

3.1 Description:

Magnetometer measurements (100–200 Hz bandwidth) within 10-km range of several vertical shaft emplaced UGTs (20-150 kt); also, within 1.25 km of the Hunters Trophy effects test and 0.5 km from the Nonproliferation Experiment (“chemical kiloton”).

3.2 Summary of Results:

1. An EMP signal (10s–100s of pT) usually detected; 1-40 Hz frequency band pass; range less than 10 km; strength falls off roughly with inverse cube of distance (**suggests a magnetic dipole source**)
2. Smooth-shaped pulse from the nuclear explosions that looks much different, and larger than from the nonproliferation experiment (NPE) chemical explosion (**suggests a useful discriminator of nuclear from chemical explosions**)

Vertical magnetic field data taken by Sweeney during five underground nuclear explosions and one underground chemical explosion is shown in Figure 1. The name of each test and the slant range distance of the magnetometer are indicated. All traces show 2 s of data sampled at 100 to 200 Hz with the zero time of the test indicated.

[1] J. Sweeney, *Low Frequency Electromagnetic Measurements as a Zero-Time Discriminant of Nuclear and Chemical Explosions–OSI Research Final Report*, LLNL UCRL-ID-126780 (December 1996).

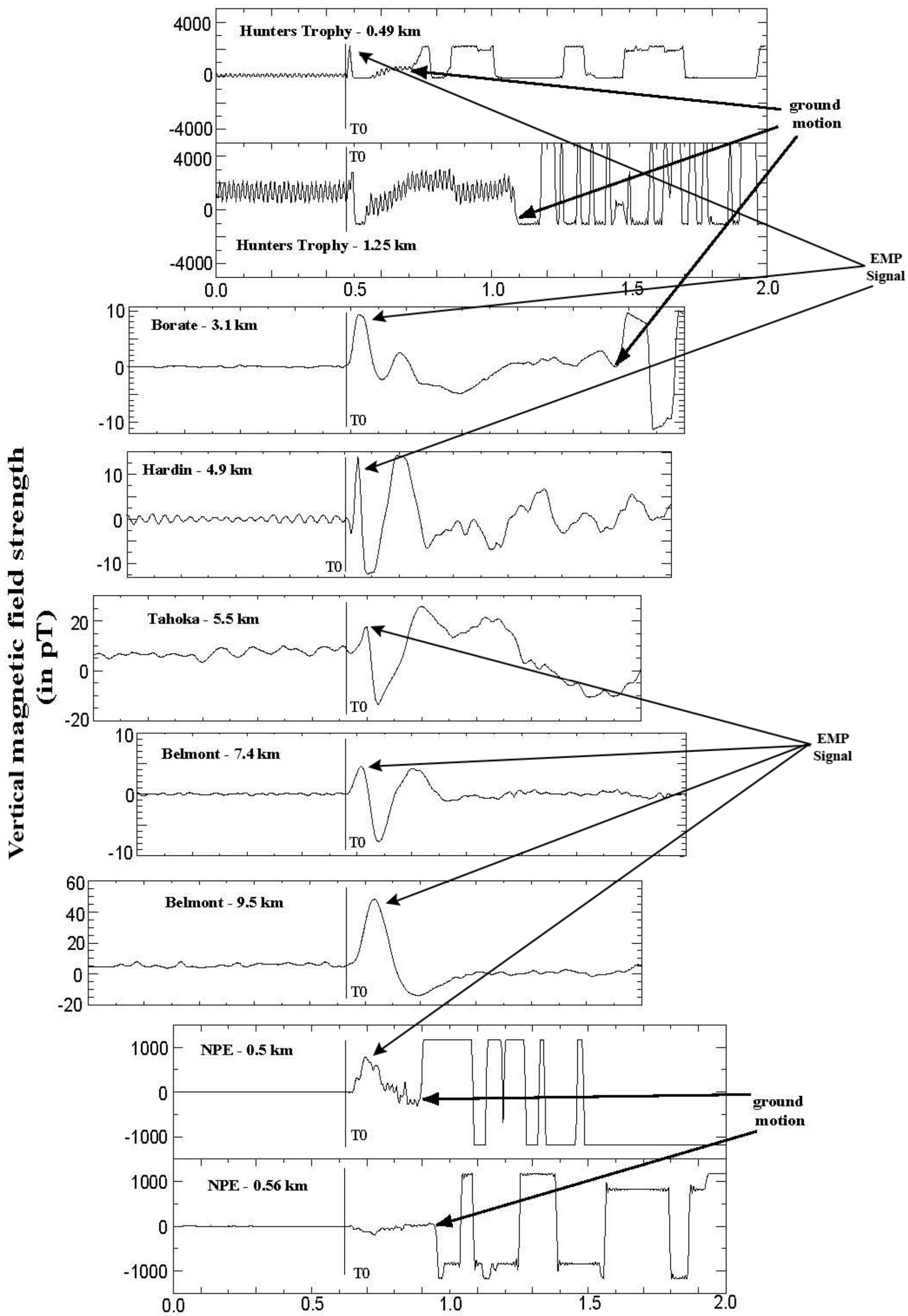

Figure 1: Vertical magnetic field data taken during six underground nuclear explosions (top seven traces) and one underground chemical explosion (bottom two traces) (from Sweeney, 1996)

4. ZABABAKHIN INSTITUTE COMPUTATIONS[2]

First paper (2001): Compares computations of magnetic dipole effect from a 1-kt underground chemical explosion versus a 1-kt fully coupled nuclear explosion in quartzite

Second paper (2004): Compares computations of 1-kt underground nuclear explosions in various environments including cavities for seismic decoupling

4.1 Zababakhin Paper #1: Comparison of a One-Kiloton Chemical and a One-Kiloton Nuclear Underground Explosion

- Nuclear magnetic moment ~100x chemical
- Nuclear magnetic moment ~4 x 10^4 Amp-m^2
- Nuclear pulse is smooth, duration <1 s, versus oscillatory pulse for chemical

Therefore:

- o Suggests ELF measurements useful as a close-in discriminator between chemical and nuclear underground explosions

4.2 Zababakhin Paper #2: Comparison of One-Kiloton Nuclear Explosions in Underground Cavities

- Magnetic moment increases ~100x as cavity size increases
- Continues to increase even beyond the Latter criterion seismic decoupling limit

Therefore:

- o Suggests ELF measurements useful to discriminate decoupled (seismically) from fully coupled underground explosions

[2] V.N. Nogin, et al., *J App Mechanics Technical Physics (2001, 2004)*; work supported by the International Science and Technology Center.

5. SCALED ESTIMATES OF UGT ELF FIELDS

5.1 Model Assumptions[3]

5.1.1 Spherically symmetric plasma source created by an underground nuclear explosion (fully coupled)

Magnetic dipole anti-parallel to B_0:

Magnetic dipole moment: $M = (2\pi/\mu_0)\, B_0 r_c^3$,

where: $\mu_0 = 4\pi \times 10^{-7}$; $B_0 = 0.5 \times 10^{-4}$ T; r_c = plasma cavity radius

Quasi-static ($\omega \rightarrow 0$) magnetic dipole field:

$B = (B_0 r_c^3)/r^3$, r = detection range parallel to magnetic moment

5.1.2 Plasma bubble scaled radius = CORRTEX strong shock scaled radius

$r_{COR}(m) = 6.29 \times W(kt)^{1/3}[\Delta t_{shock}(ms) \times W(kt)^{-1/3}]^{0.475}$ (NTS)

Assume $\Delta t_{bubble} = \Delta t_{shock} \approx 1$ ms

Therefore,

$r_c(m) = 6.3 \times W(kt)^{1/3}$ (NTS)

For other materials (e.g., hard rock), scale by $(\text{density})^{-1/3}$:

Therefore,

$r_c(m) = 5.5 \times W(kt)^{1/3}$ (Hard Rock)

---

[3] P.J. Ebert, *Non-Intrusive Verification*, UCRL-101542 (July 1989).

5.2 Estimated Magnetic Moments

Estimated magnetic moments are provided in Table 1 as a function of yield for fully coupled and seismically decoupled (i.e., cavity) cases. Note that the peak magnetic moment for 1 kt fully coupled in hard rock estimated using the simple quasi-static magnetic dipole model agrees well with the more complex, time-dependent Zababakhin calculated value. The estimated magnetic moment for 1 kt in a cavity (i.e., decoupled seismically) is larger than the Zababakhin result, possibly because the simple quasi-static magnetic dipole model neglects effects on conductivity near the air-hard rock cavity boundary.

Table 1: Estimated magnetic moments with and without decoupling

Coupled			Decoupled		
Yield (kt)	CORRTEX Radius[a] (m)	MagMom[b] (10^4 A-m^2)	Latter Radius[c] (m)	MagMom[b] (10^4 A-m^2)	Equiv Coupled Yield[a] (kt)
1.0	5.5	4.2 (4.2*)	22	266 (173*)	~50
0.1	2.55	0.42	10.2	26.6	~5
0.01	1.18	0.042	4.74	2.66	~ 0.5

Notes: a. Fully coupled magnetic bubble radius (hard rock): r_c (m) = 5.5 x W (kt)$^{1/3}$ (CORRTEX strong shock scaling)
b. M (A-m^2) = $(2\pi/\mu)\, B_0\, r^3$ (m); $\mu = 4\pi \times 10^{-7}$; $B_0 = 0.5 \times 10^{-4}$ T
c. Latter decoupling radius: r_{Lat} (m) ≈ 22 x $W^{1/3}$ (kt) (hard rock); assumes $r_c = r_{Latter}$ (plasma bubble fills the cavity)
*Zababakhin model calculations

5.3 Estimated ELF Detection Range

Example: W = 1 kt, r = 1 km range (NTS scaling)

Therefore:

B = 12.5 pT (model estimates)

Natural background ~ 2-3 pT (measured)[4]

Estimated signal/background ~ 6x

Maximum range (@ signal/bg = 1) = 1.82 km

Estimates of ELF detection range as a function of yield from J. Sweeney[4] and quasi-static model calculations are provided in Table 2. Low-yield (<<1 kt) ELF detection would require sensitive magnetometers placed within 1 km of GZ.

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[4] J. Sweeney, *Low Frequency EMP and Explosions*, LLNL-PRES-462992 (December 2010)

Table 2: Estimated ELF detection range

Yield (kt)	Detection Range (km)	
0.01	0.39	(0.41–0.54)[5]
0.1	0.84	(0.87–1.16)[5]
1.0	1.82	(1.87–2.50)[5]

5.4 Application to Transparency (or Confidence Building) at Known (or Suspect) Test Sites

The above estimates indicate two limiting cases:

1. Fully coupled nuclear explosions → strong seismic, weak ELF signals
2. Decoupled nuclear explosions → weak seismic, strong ELF signals

Therefore:

- In combination, close-in seismic and ELF monitoring would bracket fully coupled and decoupled underground nuclear explosions.
- In combination, close-in seismic and ELF monitoring could be used for close-in transparency (or confidence building) measures at known (or suspect) test sites.

[5] J. Sweeney, *Low Frequency EMP and Explosions*, LLNL-PRES-462992 (December 2010)

6. SUMMARY AND RECOMMENDATIONS

6.1 Summary

1. Previous experiments and calculations suggest that the magnetic bubble, and the resulting induced B-field transient, may be a useful discriminator of underground nuclear explosions, including in the presence of cavity decoupling.
2. The nature of the effect (low frequency (ELF), close-in range (< 10 km)) also suggests that it may be useful for test site transparency (or confidence building) at known test sites (or suspect sites) without revealing sensitive or classified nuclear weapons information.
3. Close-in monitoring, including both seismic and ELF detection, could be developed under bilateral or P-5 cooperative agreements.

6.2 Recommendations

6.2.1 ELF EMP from Underground Nuclear Explosions: Development Path

Approach: Treat as if fielding a series of diagnostic detector experiments on an underground nuclear effects test, in this case, the measurement of ELF EMP.

Understand the Source Term	Understand the Signal
1. Collect relevant nuclear test ELF data (COMPLETE??) 2. Make order-of-magnitude (scaling) estimates of the magnetic bubble EMP signal (COMPLETE??) 3. Develop a more complex model of the bubble EMP source (for example comparable to the Zababakhin models) Compare with Sweeney data from Hunters Trophy and the NPE 4. Validate the source model using laser pulse power experiments	1. Model the propagation of the ELF signal through the ground (i.e., dispersion, range, e.g., Sommerfeld solutions) 2. Generate Green's functions for various source-receiver pathways, conductivities, etc. to use with source models 3. Investigate (calculationally) the value, if any, of adding a buried cable near GZ as a signal pathway (or other tricks to get a stronger signal from the source to the receiver)
Design the Detection System	**Field Calibration Experiments**
1. Model the receivers, geometry, data processing algorithms, etc, to optimize the receiver system with respect to lowering the detectable yield and increasing the detection range 2. Set receiver BW, sensitivity, etc. 3. Select desired geometry of a sparse array of receivers 4. Select signal processing algorithms (i.e., coherent detection, background suppression) 5. Estimate natural back-grounds from existing VLF lightning arrays	1. Tailor available EMP simulators to extract ELF/VLF pulses to benchmark the receiver system design at existing EMP test facilities 2. Deploy receivers at a realistic site to examine manmade backgrounds, (e.g., Nevada Test Site [NTS]) 3. Participate in the planned shock physics experiments (SPE) 4. Design/develop a very low frequency (VLF)/ELF pulsar to serve as an underground calibration source 5. Carry out underground (in tunnels, etc.) pulsar calibration experiments

APPENDIX A. ABBREVIATIONS AND ACRONYMS

CORRTEX	Continuous Reflectometry for Radius-Time Experiments
BW	bandwidth
ELF	extremely low frequency
EMP	electromagnetic pulse
MHD	magnetic hydrodynamic
NPE	nonproliferation experiment
NTS	Nevada Test Site
SPE	shock physics experiment
UGT	underground test
VLF	very low frequency

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